A compendium of logarithmic corrections in AdS/CFT

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Eurostrings 2024

Southampton

September 6 2024

2312.08909 + to appear

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ODYSSEUS
Top science in Flanders

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Motivation

Supersymmetric localization allows for the exact calculation of physical observables in supersymmetric QFTs.

Apply this tool to SCFTs with holographic duals in string and M-theory.

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Goal: Describe recent progress on these topics for 3d SCFTs with AdS_4 duals in M-theory. Focus on $\log N$ corrections.

Plan

- Motivation ✓
- Supersymmetric partition functions
- Log corrections from supergravity
- The unbearable lightness of the KK scale
- Breaking supersymmetry: black holes and thermal observables
- Outlook

Supersymmetric partition functions

[Aharony,Bergman,Jafferis,Maldacena]; [Kapustin,Willett,Yaakov]; [Drukker,Mariño,Putrov]; [Mariño,Putrov]; [Fuji,Hirano,Moriyama]; [Herzog,Klebanov,Pufu,Tesileanu]; [Benini,Zaffaroni]; [Closset,Kim]; [Benini,Hristov,Zaffaroni]; [Liu,Pando Zayas,Rathee,Zhao]; [NPB,Hong,Reys]; [Nosaka]; [Hatsuda]; [Hristov]; [Chester,Kalloor,Sharon]; [Bhattacharya^2,Minwalla,Raju]; [Kim]; [Choi,Hwang,Kim]; [Choi,Hwang]; [Nian,Pando Zayas]; [NPB,Choi,Hong,Reys]; [NPB,De Smet,Hong,Reys,Zhang]

ABJM and holography

The ABJM theory: $\mathrm{U}(N)_k \times \mathrm{U}(N)_{-k}$ 3d CS-matter theory with two pairs of bi-fundamental chirals $(A_{1,2}, B_{1,2})$ and superpotential

$$\mathcal{W} = \mathrm{Tr}(A_1 B_1 A_2 B_2 - A_1 B_2 A_2 B_1)\,.$$

For $k > 2$ it has $\mathcal{N} = 6$ supersymmetry and $\mathrm{SU}(4)_R \times \mathrm{U}(1)_b$ global symmetry. Describes N M2-branes on $\mathbb{C}^4/\mathbb{Z}_k$.

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- In the limit of fixed k and large N, the ABJM theory is dual to the M-theory background $\mathrm{AdS}_4 \times S^7/\mathbb{Z}_k$

$$(L/\ell_{\mathrm{P}})^6 \sim k\,N\,.$$

- The path integral on various compact three-manifolds can be computed by supersymmetric localization and reduced to a matrix model. This in turn can be analyzed with various analytic and numerical techniques, particularly in the large N limit.

ABJM on S^3 - An Airy Tale

The path integral on a squashed S^3 with real mass deformation can be computed by supersymmetric localization and reduces to a matrix model.

$$Z_{S^3}(N,k,m_a,b) \overset{!}{=} e^{\mathcal{A}(k,\Delta,b)} C^{-\frac{1}{3}} \mathrm{Ai}[C^{-\frac{1}{3}}(N-B)] + \mathcal{O}(e^{-\sqrt{N}}) \,,$$

with fixed k, large N and

$$C = \frac{2}{\pi^2 k}\frac{(b+b^{-1})^{-4}}{\prod_{a=1}^4 \Delta_a} \,, \quad B = \frac{k}{24} - \frac{1}{12k}\sum_{a=1}^4 \frac{1}{\Delta_a} + \frac{1-\frac{1}{4}\sum_a \Delta_a^2}{3k(b+b^{-1})^2 \prod_{a=1}^4 \Delta_a} \,,$$

and

$$\Delta_1 = \frac{1}{2} - \mathrm{i}\,\frac{m_1+m_2+m_3}{b+b^{-1}} \,, \qquad \Delta_2 = \frac{1}{2} - \mathrm{i}\,\frac{m_1-m_2-m_3}{b+b^{-1}} \,,$$
$$\Delta_3 = \frac{1}{2} + \mathrm{i}\,\frac{m_1+m_2-m_3}{b+b^{-1}} \,, \qquad \Delta_4 = \frac{1}{2} + \mathrm{i}\,\frac{m_1-m_2+m_3}{b+b^{-1}} \,.$$

The large N expansion takes the explicit form

$$-\log Z_{S^3} = \frac{2}{3\sqrt{C}} N^{\frac{3}{2}} - \frac{B}{\sqrt{C}} N^{\frac{1}{2}} + \frac{1}{4}\log N - \mathcal{A} + \frac{1}{4}\log\frac{32}{k} + \mathcal{O}(N^{-\frac{1}{2}}) \,.$$

The TTI and the SCI

The topologically twisted index (TTI) is the partition function of 3d $\mathcal{N}=2$ SCFTs on $S^1 \times \Sigma_{\mathfrak{g}}$. Supersymmetry is preserved by a topological twist on $\Sigma_{\mathfrak{g}}$. The path integral can be reduced to a matrix integral and computed at large N and fixed k. The free energy $F_{S^1\times\Sigma_{\mathfrak{g}}} = -\log Z_{S^1\times\Sigma_{\mathfrak{g}}}$, takes the form:

$$F_{S^1\times\Sigma_{\mathfrak{g}}}(\mathfrak{n},\Delta) = g_{\frac{3}{2}}(\mathfrak{n},\Delta)N^{\frac{3}{2}} + g_{\frac{1}{2}}(\mathfrak{n},\Delta)N^{\frac{1}{2}} + \frac{1-\mathfrak{g}}{2}\log N + \dots$$

The holographic dual is the (Euclidean) supersymmetric static Reissner-Nordström BHs in AdS$_4$. The TTI computes its entropy.

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The superconformal index (SCI), or $S^1 \times_\omega S^2$ partition function, counts $\frac{1}{16}$-BPS operators in 3d $\mathcal{N}=2$ SCFTs. It is useful to consider the Cardy-like limit $\omega \to 0$. For the ABJM theory at fixed k and large N one finds

$$F_{S^1\times_\omega S^2}(\omega) = h_{\frac{3}{2}}(\omega)N^{\frac{3}{2}} + h_{\frac{1}{2}}(\omega)N^{\frac{1}{2}} + \frac{1}{2}\log N + \dots$$

The SCI captures the entropy of supersymmetric AdS$_4$ Kerr-Newman black holes.

Log corrections from supergravity

[Camporesi,Higuchi]; [Vassilevich]; [Sen]; [Bhattacharyya,Grassi,Mariño,Sen]; [Liu,Pando Zayas,Rathee,Zhao]; [Pando Zayas,Xin]; [Hristov,Reys]; [David,Godet,Liu,Pando Zayas]; [NPB,David,Hong,Reys,Zhang]

Log corrections

There are log corrections to the (semi-classical) BH entropy ($\mathrm{Area} \gg G_{\mathrm{N}}$)

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Ashoke Sen: s_0 can be computed by 1-loop contributions of all "light" fields in the BH background. Agreement with string theory UV calculations for BPS black holes. "IR window into UV physics!"

Example: 4d Schwarzschild in GR + n_s fields of spin $s = 0, \frac{1}{2}, 1, \frac{3}{2}$.

$$s_0 = \frac{1}{90}\left(2n_0 + 7n_{\frac{1}{2}} - 26n_1 - \frac{233}{2}n_{\frac{3}{2}} + 289\right) .$$

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Here: Log corrections in AdS$_4$, i.e. $\log \frac{L^2}{G_{\mathrm{N}}}$ with $L^2 \gg G_{\mathrm{N}}$.

$$F_{S^3}(b,\Delta) = f_{\frac{3}{2}}(b,\Delta)N^{\frac{3}{2}} + f_{\frac{1}{2}}(b,\Delta)N^{\frac{1}{2}} + \frac{1}{4}\log N + \dots$$

$$F_{S^1\times\Sigma_{\mathfrak{g}}}(\mathfrak{n},\Delta) = g_{\frac{3}{2}}(\mathfrak{n},\Delta)N^{\frac{3}{2}} + g_{\frac{1}{2}}(\mathfrak{n},\Delta)N^{\frac{1}{2}} + \frac{1-\mathfrak{g}}{2}\log N + \dots$$

$$F_{S^1\times_\omega S^2}(\omega) = h_{\frac{3}{2}}(\omega)N^{\frac{3}{2}} + h_{\frac{1}{2}}(\omega)N^{\frac{1}{2}} + \frac{1}{2}\log N + \dots$$

The coefficient of $\log N$ does NOT depend on continuous parameters!

Heat kernel in 4d

Study the log term in the (Euclidean) path integral of GR+EFT in AdS_4 with cutoff scale Λ

$$-\log Z_{\mathrm{GR+EFT}} = S_{\mathrm{cl}}(\mathring{\phi}) + \mathcal{C} \log L\Lambda + \ldots .$$

All fields ϕ with $\mathrm{mass}_\phi < \Lambda$ contribute to $\mathcal{C}$. Use the heat kernel method to compute $\mathcal{C}$.

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Input: The kinetic operator $\mathcal{Q}_\phi$ and the number of zero modes

$$\mathcal{C} = \sum_\phi \int d^4x\sqrt{g}\, a_4(x, \mathcal{Q}_\phi) + \mathcal{C}_{\mathrm{ZM}} .$$

The Seeley-de Witt coefficient $a_4(x, \mathcal{Q}_\phi)$ depends on the background fields

$$16\pi^2 a_4(x, \mathcal{Q}_\phi) = -a_E E_4 + cW^2 + b_1 R^2 + b_2 R F_{\mu\nu} F^{\mu\nu} .$$

Straightforward to calculate $a_4(x, \mathcal{Q}_\phi)$ for massive fields of spin $\leq$ 2.

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Straightforward to calculate $a_4(x, \mathcal{Q}_\phi)$ for massive fields of spin ≤ 2.

Subtlety: It is in general hard to compute $\mathcal{C}_{\mathrm{ZM}}$. Rigorous results only for AdS$_4$ and AdS$_2 \times \Sigma_{\mathfrak{g}}$.

Massive scalar

The background: Any Euclidean solution of 4d Einstein-Maxwell theory

$$S_{\mathrm{EM}} = -\frac{1}{16\pi G_{\mathrm{N}}} \int d^4x \sqrt{g} \left[R + \frac{6}{L^2} - F_{\mu\nu} F^{\mu\nu} \right] .$$

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The field: Scalar field ϕ of mass m, charge q, and action

$$S_\phi = \int d^4x \sqrt{g}\; \phi[-\mathcal{D}^\mu \mathcal{D}_\mu + m^2]\phi \,, \qquad \mathcal{D}_\mu = \nabla_\mu - \mathrm{i} q A_\mu \,.$$

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The Seeley-de Witt coefficients:

$$a_{\mathrm{E}} = \frac{1}{360} \,, \quad c = \frac{1}{120} \,, \quad b_1 = \frac{1}{288}[(mL)^2 + 2]^2 \,, \quad b_2 = \frac{1}{144}(qL)^2 \,.$$

Seeley-de Witt Coefficients

Bulk contribution to the SdW coefficient for massive fields of spin ≤ 2.

spin	mass	a_E	c	b_1
0	$(mL)^2 = -2$	$\frac{1}{360}$	$\frac{1}{120}$	0
0	m	$\frac{1}{360}$	$\frac{1}{120}$	$\frac{1}{288}\left((mL)^2+2\right)^2$
1/2	0	$-\frac{11}{720}$	$-\frac{1}{40}$	0
1/2	m	$-\frac{11}{720}$	$-\frac{1}{40}$	$\frac{1}{144}(mL)^2\left((mL)^2-2\right)$
1	0	$\frac{31}{180}$	$\frac{1}{10}$	0
1	m	$\frac{31}{180}+\frac{1}{360}$	$\frac{1}{10}+\frac{1}{120}$	$\frac{1}{288}\left(3(mL)^4-12(mL)^2+4\right)$
3/2	$mL=1$	$\frac{589}{720}$	$\frac{137}{120}$	0
3/2	m	$\frac{589}{720}-\frac{11}{720}$	$\frac{137}{120}-\frac{1}{40}$	$\frac{1}{72}\left((mL)^4-8(mL)^2+11\right)$
2	0	$\frac{571}{180}$	$\frac{87}{20}$	0
2	m	$\frac{571}{180}+\frac{31}{180}+\frac{1}{360}$	$\frac{87}{20}+\frac{1}{10}+\frac{1}{120}$	$\frac{5}{288}\left((mL)^4-8(mL)^2+8\right)$

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Important: For $s = 1, \frac{3}{2}, 2$ massless fields need ghosts, while massive fields need Stückelberg "friends".

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Study 4d sugra backgrounds and impose that $\mathcal{C}$ does not depend on continuous parameters.

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- AdS-Taub-NUT ($\mathrm{U}(1) \times \mathrm{U}(1)$ squashed S^3)

$$
\begin{aligned}
ds^2 &= f_1^2 dx^2 + f_2^2 dy^2 + \frac{1}{f_1^2}(d\psi + y^2 d\phi)^2 + \frac{1}{f_2^2}(d\psi + x^2 d\phi)^2 \,, \\
f_1^2 &= \frac{L^2(y^2 - x^2)}{(x^2-1)(b^4 - x^2)} \,, \qquad f_2^2 = \frac{L^2(y^2 - x^2)}{(y^2-1)(y^2 - b^4)} \,, \\
F &= d\left[\frac{b^4 - 1}{L(x+y)}(d\psi - xy d\phi)\right] \,.
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- Euclidean Romans solution (Euclidean susy RN black hole in AdS_4)

$$ds^2 = \left[\left(\frac{r}{L} + \frac{\kappa L}{2r}\right)^2 - \frac{q^2}{4r^2}\right] d\tau^2 + \left[\left(\frac{r}{L} + \frac{\kappa L}{2r}\right)^2 - \frac{q^2}{4r^2}\right]^{-1} dr^2 + r^2 ds^2_{\Sigma_\mathfrak{g}} \,,$$

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$$F = \frac{q}{r^2} d\tau \wedge dr - \kappa L \mathrm{vol}_{\Sigma_\mathfrak{g}} \,.$$

This leads to the strong constraint

$$\boxed{c^{\mathrm{tot}} = b_1^{\mathrm{tot}} = b_2^{\mathrm{tot}} = 0}$$

Top-down KK supergravity

Consider 11d sugra on S^7 dual to the ABJM theory at $k = 1$ and large N.

The resulting 4d $\mathcal{N} = 8$ gauged sugra is not a standard EFT, it has infinitely many fields!

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Organize the KK modes into $\mathcal{N} = 8$ multiplets and compute the SdW coefficients.

spin	Dynkin label	Δ
2	$(n,0,0,0)_{n\geq 0}$	$3+n/2$
3/2	$(n,0,0,1)_{n\geq 0}$ $(n-1,0,1,0)_{n\geq 1}$	$5/2+n/2$ $7/2+n/2$
1	$(n,1,0,0)_{n\geq 0}$ $(n-1,0,1,1)_{n\geq 1}$ $(n-2,1,0,0)_{n\geq 2}$	$2+n/2$ $3+n/2$ $4+n/2$
1/2	$(n+1,0,1,0)_{n\geq 0}$ $(n-1,1,1,0)_{n\geq 1}$ $(n-2,1,0,1)_{n\geq 2}$ $(n-2,0,0,1)_{n\geq 2}$	$3/2+n/2$ $5/2+n/2$ $7/2+n/2$ $9/2+n/2$
0_+	$(n+2,0,0,0)_{n\geq 0}$ $(n-2,2,0,0)_{n\geq 2}$ $(n-2,0,0,0)_{n\geq 2}$	$1+n/2$ $3+n/2$ $5+n/2$
0_-	$(n,0,2,0)_{n\geq 0}$ $(n-2,0,0,2)_{n\geq 2}$	$2+n/2$ $4+n/2$

Massive $\mathcal{N} = 8$ supermultiplets at KK level n.

Top-down KK supergravity

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For the total a_E coefficient one finds the divergent sum

$$a_E = -\frac{1}{72}\sum_{n=0}^{\infty}(n+1)(n+2)(n+3)^2(n+4)(n+5) =: \sigma\,.$$

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$$a_E = -\frac{1}{72}\sum_{n=0}^{\infty}(n+1)(n+2)(n+3)^2(n+4)(n+5) =: \sigma \, .$$

Unclear how to regulate this sum. If we take $\sigma = -1/3$ we find

$$\boxed{\mathcal{C}(\partial\mathcal{M}) = -\frac{1}{4}\chi(\mathcal{M})} \, .$$

Perfect agreement with all susy localization results in the ABJM theory!

Similar results for a number of other AdS_4 vacua in M-theory with explicitly known KK spectra.

The unbearable lightness of the KK scale

Assumption: The UV completion of GR+EFT in AdS_4 is holographic, i.e. there is a dual family of 3d CFTs with a suitable large N limit.

Consider such a GR+EFT with **finitely** many fields and a cutoff Λ such that $L\Lambda \sim N^\alpha$ with $\alpha > 0$ (or $L\Lambda \sim \lambda^\beta$ for a marginal coupling λ).

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The free energy of the 3d CFT on a compact Euclidean manifold takes the form

$$\log Z_{\mathrm{CFT}} = F_0 + \mathcal{C}_{\log} \log N \,,$$

where F_0 contains all positive powers of N.

The unbearable lightness of the KK scale

Assumption: The UV completion of GR+EFT in AdS_4 is holographic, i.e. there is a dual family of 3d CFTs with a suitable large N limit.

Consider such a GR+EFT with **finitely** many fields and a cutoff Λ such that $L\Lambda \sim N^{\alpha}$ with $\alpha > 0$ (or $L\Lambda \sim \lambda^{\beta}$ for a marginal coupling λ).

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$$\log Z_{\rm CFT} = F_0 + \mathcal{C}_{\log} \log N\,,$$

where F_0 contains all positive powers of N.

If $\mathcal{C}_{\log}$ does **not** depend on continuous parameters (mass, squashing, angular velocity) then the SdW coefficients of the 4d bulk theory are constrained to obey

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A new tool to delineate the landscape of scale separated AdS_4 vacua?

Black holes and thermal observables

[Witten]; [Horowitz,Myers]; [NPB,Charles,Hristov,Reys]; [NPB,Hong,Reys];
[Iliesiu,Koloğlu,Mahajan,Perlmutter,Simmons-Duffin]; [Luo,Wang]; [Benjamin,Lee,Ooguri,Simmons-Duffin]

BHs and thermal observables

Using the results above we can also compute the leading corrections to the entropy of any large asymptotically $\text{AdS}_4 \times S^7/\mathbb{Z}_k$ black hole.

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Example: AdS-Schwarzschild black hole

$$S_{\mathrm{Sch}}^{\mathrm{ABJM}} = \frac{2\pi r_+^2}{L^2}\frac{\sqrt{2k}}{3}\left(N^{\frac{3}{2}} + \frac{16-k^2}{16k}N^{\frac{1}{2}}\right) + \frac{2\pi}{\sqrt{2k}}N^{\frac{1}{2}} - \frac{1}{2}\log N$$

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Consider a 3d CFT on $S^1_\beta \times \mathbb{R}^2$. The vev of the stress-energy tensor and the thermal free energy are

$$\langle \mathcal{T}^{00} \rangle = \frac{2}{3}\frac{b_{\mathcal{T}}}{\beta^3}\,, \qquad F_{S^1_\beta \times \mathbb{R}^2} = \frac{f_{\mathcal{T}}}{\beta^3}\,, \qquad 3 f_{\mathcal{T}} = b_{\mathcal{T}}\,.$$

To compute $f_{\mathcal{T}}$ in the bulk use the "AdS soliton". For the ABJM theory we find

$$b_{\mathcal{T}} = -\frac{8\pi^2\sqrt{2k}}{27}N^{\frac{3}{2}} + \frac{\pi^2(k^2-16)}{27\sqrt{2k}}N^{\frac{1}{2}} + 0 \times \log N \ldots\,.$$

Somewhat surprisingly we find that to this order at large N $b_{\mathcal{T}} = -\frac{\pi^3}{72}C_{\mathcal{T}}$!

Summary

- Presented exact results for the large N limit of the partition function of the ABJM theory on S^3, $S^1 \times \Sigma_{\mathfrak{g}}$, and $S^1 \times_\omega S^2$ focusing on the $\log N$ contribution.
- Discussed how these log terms can be reproduced by supergravity and string/M-theory via AdS/CFT.
- Important for understanding the entropy of supersymmetric AdS_4 Reissner-Nordström and Kerr-Newman black holes.
- New constraints on gravity + EFTs in AdS?
- Application of these results to non-supersymmetric black hole thermodynamics and CFT thermal observables.

Outlook

Results I did not discuss

- Large N supersymmetric partition functions for other 3d $\mathcal{N} = 2$ holographic SCFTs via supersymmetric localization.
- Similar logarithmic correction results for the holographically dual AdS_4 backgrounds in string/M-theory.
- Similar large N and holographic results for 3d $\mathcal{N} = 2$ SCFTs arising from M5-branes (class $\mathcal{R}$ SCFTs).

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Some open questions

- A better understanding of the simplicity and universality of the logarithmic corrections?
- Derivation from (or lessons for) type IIA string theory and M-theory?
- OSV-type conjecture for AdS black holes?
- Application of the "unbearable lightness" constraint to candidate scale separated AdS_4 vacua?

thank you
gracias
merci
danke
obrigado
謝謝
teşekkür ederim
ngiyabonga
go raibh maith agat
mochchakkeram
sukriya
kop khun krap
terima kasih
bedankt
dziękuję
спасибо
arigatô
dakujem
grazie
tapadh leat
dank je
감사합니다
ευχαριστώ
мерси
ありがとう